Stellar Planet Survey-STEPS

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Abstract. The Stellar Planet Survey (STEPS) is an astrometric search for planets around nearby stars. The advantages of astrometry are (1) the technique is more sensitive to detecting planets with larger planet-to-star separations, i.e. stellar systems similar to ours; and (2) the planet-to-star mass ratios are measured directly, independent of the system inclination angles. Since, in contrast, radial velocity searches are more sensitive to systems with smaller separations, the majority of known planets are close to their stars: only 25% of planets known today have orbits beyond 1.5 AU, and none are as distant as Jupiter. Our search for *solar-like* systems now has a temporal baseline of 4 years, and has yielded preliminary evidence for low-mass companions to some of our targets.

1. Introduction

In the last seven years, planetary systems research has blossomed with the discovery and characterization of planets around other stars (Mayor & Queloz 1995; Marcy & Butler 1996; Cochran et al., 1997; Noyes et al. 1997). After centuries of intense speculation and anticipation (e.g., Black 1995), we finally have reproducible, hard evidence that planets exist elsewhere in the universe. The companions that have been discovered to date appear to consist of a mixture of gas giant planets, similar to Jupiter and Saturn, and brown dwarf stars (Boss 1996). The discoveries of these theoretically-predicted, low mass companions to solar-type stars are exciting, not only in their own right (Burrows et al. 2001 and references therein), but also for what their existence implies about even lower mass companions that must also be waiting to be discovered: icy planets like Uranus and Neptune, and rocky planets like Earth and Venus. The ultimate goal of the search for extrasolar planets is to discover Earth-like planets orbiting within the habitable zone of their stars, planets capable of supporting life, planets that we will surely be driven to study in ever-greater detail.

Few of the known systems are good candidates for sheltering Earth-like planets. For example, 51 Peg, with a $^1/_2$ Jupiter-mass (M_J) planet at 0.05 AU from the star, is not at all likely to harbor an Earth. Because theorists cannot conceive of forming gas giant planets in the inferno of a protoplanetary disk at 0.05 AU (Boss 1995), the best explanation for 51 Peg's planet is inward orbital migration following its formation much farther from its star (Lin, Bodenheimer, & Richardson 1996). This inferred inward migration would have led to the destruction of any Earths that planet encountered along the way.

STEPS' astrometry favors the detection of long-period systems. Theoretical models of solar system formation (e.g., Wetherill 1990) are based on the premise that rocky, Earth-like planets form closer to the star than ice-rich giant planets, because ices could not remain as solids in the hot inner solar nebula. Accordingly, we expect to find Earth-like planets orbiting inside Jupiter-like planets, at least whenever the Jupiter-like planets have orbits similar to those of Jupiter and Saturn, i.e., from 5 AU to 10 AU, in solar-type systems. We do not know yet whether *solar-like* systems around lower-mass stars exist.

M stars, by far the most numerous in our galaxy, are largely unexplored for planets. This is in part a selection effect of the radial velocity searches. To date there is only one M star, Gl 876 (Marcy et al. 2001), among the ~ 80 stars known to have planetary systems. The STEPS program, in contrast, contains only M stars as its targets. STEPS is sensitive enough to thoroughly examine these stars for planets of M_J and larger in multi-year orbits. Planetary formation theory has made dramatic advances already from discoveries in solar-type systems. The field of planetary systems around low-mass stars awaits similar results.

2.   Results

2.1.   Observations to Date

We have regularly observed 30 target stars with the STEPS CCD camera on the Palomar 200" telescope since 1998. The targets have 5-20 reference stars each, astrometric signals with an average of 2.7 milliarcseconds (mas) and a minimum of 0.8 mas for a M_J planet in a 10-y orbit, and are not so bright that they saturate the detector in 1-min exposures in $1''$ seeing. Note that the expected signal scales directly with the planet mass.

STEPS routinely obtains nightly precisions of 0.25 - 0.4 mas per 20 minute observation. The level of systematic errors from night-to-night for sources observed over multi-night runs is $\lesssim 1$ mas for 60% of the targets, and $\lesssim 2$ mas for 80% of the targets. The long-term, run-to-run standard deviation – noise plus possible signal – averages 1.6 mas in RA and 2.2 mas in DEC, after fitting for parallax and proper motion. STEPS proper motion and parallax measurements agree to within a few percent of the published values for the best-observed sources.

Figure 1 (left) shows the present sensitivity of our targets to giant planets, assuming that the measured signals consist of random noise, and accounting for the parallax and mass of the stars and duration of the observational baseline. Any source above the curves is inconsistent with the astrometric data at the 3σ level. In other words, our data rules out the existence of a planet in the space above the curves. These curves are approximations to the more accurate periodograms. The curves will drop toward lower minimum mass sensitivity as the STEPS temporal baseline is extended. In some cases (e.g., Gl 164, see below), the data appears to be consistent with an acceleration, indicating a long period giant planet or brown dwarf companion. Figure 1 (right) shows the sensitivity to giant planets after 10 years, assuming a systematic noise floor of 1 mas.
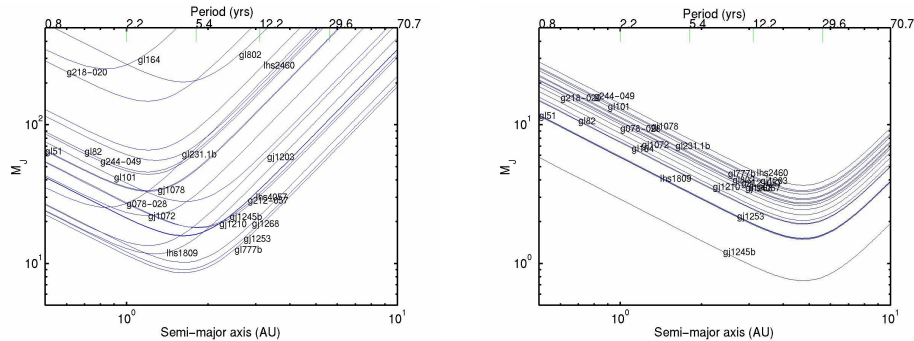
Figure 1. The plot on the left shows for each target the current sensitivity of the STEPS data to the detection of planets in the parameter plane with mass in units of M_J in the vertical direction, and semi-major axis (bottom axis) or period (top axis) in the horizontal direction. The plot on the right shows the sensitivities that will be achieved when the current 4-yr baseline reaches 15 years.

2.2. STEPS Targets of Particular Interest

The most complex system we observe is the triple system GJ 1245ABC. This 2 Gyr-old system consists of 3 M stars and is at 4.7 pc (McCarthy et al. 1988). A and B are classified as M6e and are separated by $\sim$ 8 arcsec. The C component is believed to be M8-9 with a mass of 80 M_J and orbits A with a $\sim$ 16-yr period. A and C are separated by $\lesssim$ 0.5 $''$ and are unresolved in our data. The targets AC and B are nearly identical in color and brightness, and are in close proximity on our CCD. They therefore exhibit highly-correlated systematic effects. Upon subtracting B from AC and fitting a linear motion to account for the $\sim$ 700-year orbit of AB, we obtain the result shown in Figure 2 (left). The data reveal the orbit of AC with a good fit to the model of Harrington (1990) except that the epoch is $\sim$ 1 yr later (cf. Schroeder et al. 2000). The residuals after the AC orbit is removed from these data are $\lesssim$ 1 mas in both RA and DEC ruling out a planet of $\gtrsim$ 1 M_J with an orbit of $\gtrsim$ 3 years in the AC or B systems.

Gl 164 (Figure 2, right) shows long-period acceleration consistent with a companion having mass $\gtrsim$ 40 M_J. The companion to Gl 164 is potentially the lowest mass brown dwarf detected. The period cannot yet be precisely measured because the observing baseline is only 700 days. Further observations are required to determine the periods and masses of the companions.

3. Conclusions

As our sensitivity and baseline increase we accumulate evidence for companions to some of the M star STEPS targets. Further observations will confirm or refute the results. Multi-M_J planets in several year orbits are ruled out around others of our targets.
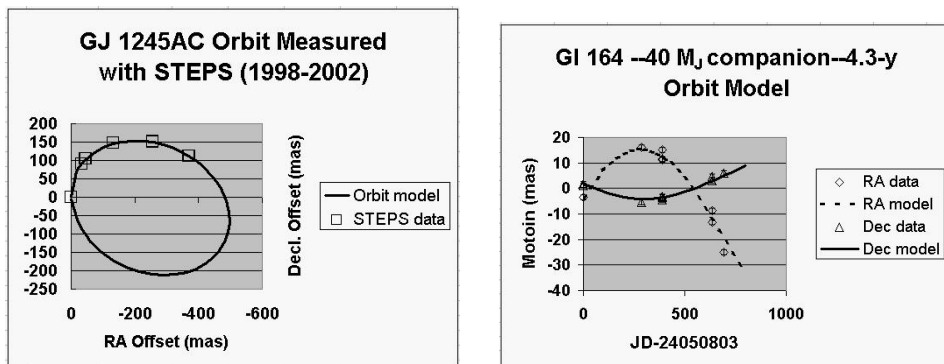
Figure 2.   Left: STEPS data taken with the Palomar 200" is shown superposed on the best-fit model of the GJ 1245AC orbit. Right: Motion of Gl 164 is consistent with a low-mass companion.

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